Modeling of multiwavelength laser with saturable homogeneous gain and nonlinear loss

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Abstract
We theoretically studied the operation of a laser with homogeneous gain and nonlinear loss. Multi-wavelength operation is possible because the nonlinear loss provides an adaptive balance to the different gain values at different wavelengths.

Introduction
Stable multi-wavelength lasers are desirable in optical communication systems, fiber sensing and many applications. Normally, it is difficult to generate multi-wavelength laser with homogenous gain media such as erbium doped fibers. Cooling the homogeneous medium to low temperature can reduce homogeneous bandwidth and generate multiwavelength laser [1,2]. But it's not applicable to maintain the system to low temperature in engineering. Recently, we have experimentally demonstrated that it is possible to construct multi-wavelength erbium doped fiber lasers by incorporating nonlinear polarization rotation effect or a nonlinear optical loop mirror into the laser cavity [3,4]. In this paper, we study theoretically the operation of a laser constructed with homogeneous gain and nonlinear loss. We demonstrated that multi-wavelength lasing is possible in a homogeneous gain medium because the nonlinear loss can adaptively balance the different gain values at different wavelengths. The dependence of the laser output parameter such as the number of lasing wavelength and the power profile of the laser output as function of the laser parameters will be given.

Theoretical model
Figure 1 shows the schematic of a multi-wavelength laser which composes of a gain element, a loss, a comb filter, and an output coupler. We assume that the loss element can introduce nonlinear or intensity dependent loss into the laser cavity. For simplicity, we assume an ideal comb filter that fixes the lasing channels. The output coupler loss is included in the loss element. The labels I, II, and III in Fig. 1 indicate three different locations of the laser. At steady state, the power of every channel at point III (after the loss element) of the cavity should be equal to that at point I (before the gain element).

We assume a saturable homogenous gain model. The power inside the gain element at the i-th wavelength defined by the comb filter can be modeled by

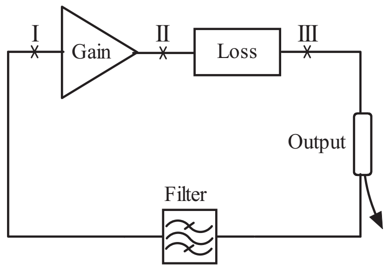

Fig.1. Schematic diagram of a multi-wavelength laser.

$$\frac{dP_i}{dz} = \frac{g_0 f_i}{1 + P_{\text{total}} / P_{\text{sat}}} P_i \tag{1}$$

where g_0 is the small signal gain coefficient and we use $G_i = exp(g_0 f_i l)$ for the small signal gain of the i-th channel, and l is the length of the gain medium. The parameters fi are the normalized gain profile with max$\{f_i\}$ = 1. In the following, we will use a Gaussian profile. The i-th channel is therefore at wavelength $i\delta\lambda$ away from the center wavelength on either side of the gain peak where $\delta\lambda$ is the mode separation. The parameter P_{sat} is the saturation power and P_{total} is the total output power of laser.

The nonlinear loss or intensity dependent loss element can be modeled as

$$dP_i / dz = (\alpha_1 + \alpha_2 P_i) P_i \tag{2}$$

where $\alpha_1 < 0$ and $\alpha_2 < 0$ are the linear and nonlinear loss coefficients, and z is the distance along the loss element. Equation (2) can be considered as the first order approximation of any intensity-dependent loss functions. In the simulation, $\alpha_1 l_l = -\ln(0.9)$, l_l is the length of loss element. Thus the small signal loss is 0.1 and α_2/α_1 is set to 10. We simulate the multiwavelength lasers by iterating Eqs. (1) and (2) until the laser reaches steady state operation.

Results and discussions
First we consider a laser with saturable homogeneous gain medium and constant loss, i.e. $\alpha_2 = 0$. Figure 1(a) shows the evolution of the gain in the laser. As the number of iterations increases, the gain curve drops until the peak of the gain profile is equal to the cavity loss. Thus only one mode can survive. The evolution will be more complicate when we replace the constant loss by a nonlinear loss. Figure 2(b) shows the variation of the

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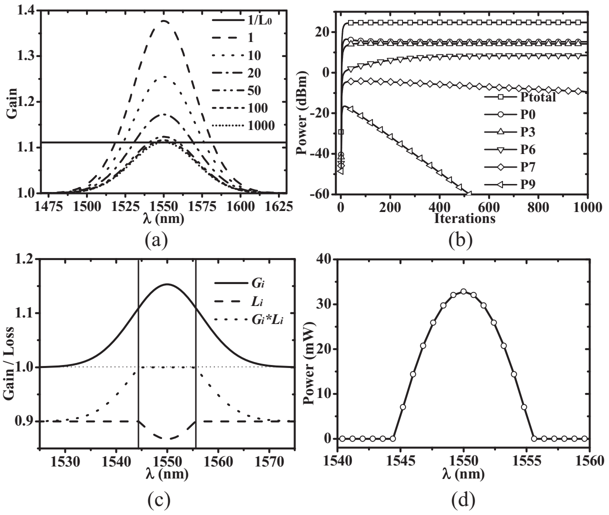

Fig. 2. (a) Evolution of the gain for a laser with saturable homogeneous gain medium and constant loss. (b) The evolution of the powers of individual channels in a laser with saturable homogeneous medium and nonlinear loss. (c) Gain and loss profiles at steady state for the laser in (b). (d) The steady state spectrum of the multiwavelength laser in (b).

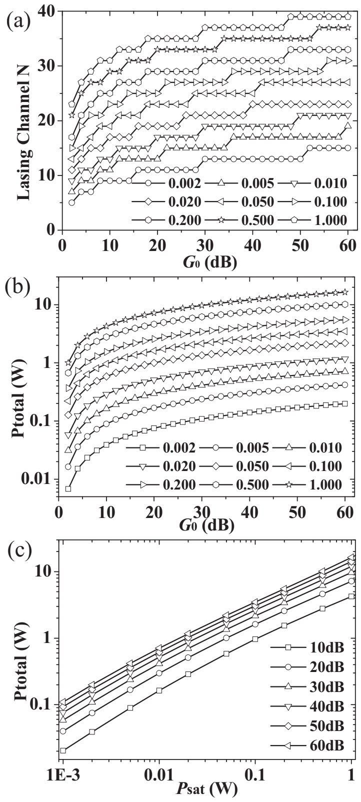

Fig. 3. (a) Variation of the number of lasing channels with the small signal gain of the center wavelength for different values of P_{sat}(in Watt). (b) Variation of the total power with the small signal gain of the center wavelength for different values of P_{sat} (in Watt). (c) Variation of the total power with the saturation power of the gain medium for different values of small signal gain.

optical powers at different modes in the multiwavelength laser as a function of iteration for a laser with saturable homogeneous medium and nonlinear loss. In the simulation, the bandwidth for the gain profile is 10 nm and the small signal gain for the center wavelength G_0 = 20 dB, and P_{sat} is 10 mW. Initially all the modes satisfying the lasing condition of gain > loss will grow. As the power in each mode grows, the loss each mode experiences will also increase because of the nonlinear response as Eq. (2) shows. The gain G_i begins to decrease due to gain saturation. Because the gain medium is homogeneous for all wavelengths, so the gain profile will drop as a whole. As a result, some of the growing modes with small f_i will begin to have their gain less than the loss. The power in these modes will begin to decay, e.g. the 7-*th* and 9-*th* modes in Fig. 2(b). Since the loss now depends on the power at each mode, the stable lasing condition of cavity gain equals loss can be satisfied by more than one mode, e.g. the 0-*th* to 6-*th* modes in Fig. 2(b). Figure 2(c) shows the gain and loss profile when the laser goes to steady state after several thousands of iterations. The loss at the wavelength which has large gain will also be large to neutralize the power. So at last, the G_i*L_i curve is equal to 1.0 in the whole range that lasing modes survived. In our simulation, there are initially 49 modes growing because their small signal gains are larger than the small signal losses, but eventually at steady state only 13 nonzero modes survive which are shown in Fig. 2(d). Thus a saturable homogeneous gain medium supports multiwavelength operation in the presence of the nonlinear loss.

Figure 3(a) shows the variation of number of lasing channel with G_0 for different values of P_{sat}. The results show that the lasing channel will increase with G_0 but the rate of increase decreases when G_0 increases. Figures 3(b) and (c) give the total output power after the loss element (point I) for different values of G_0 and P_{sat}. The variation of total power is similar to the variation of channel count. From Fig. 3(c) we can see that the total laser output power increases exponentially with P_{sat}.

Summary

From the simulations, we have shown that multi-wavelength operation for a laser with saturable homogeneous is possible if the laser incorporates a nonlinear or intensity dependent loss mechanism. The nonlinear loss adaptively balances the different gain values at different wavelength channels.

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